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RAYLEIGH WAVE AND ACOUSTIC-GRAVITY WAVE SIGNALS FROM NUCLEAR EXPLOSIONS IN THE ATMOSPHERE

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Teledyne Geotech
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RAYLEIGH WAVE AND ACOUSTIC-GRAVITY WAVE SIGNALS FROM NUCLEAR EXPLOSIONS IN THE ATMOSPHERE

FINAL TECHNICAL REPORT

BY

CARL A. NEWTON

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13. ABSTRACT

The detection of nuclear explosions in the atmosphere has posed problems to the variety of techniques used to sense the resulting disturbances. Hence, the research covered by the subject contract was directed toward the extraction of intelligence from microbarographic signals. The principal objective was to improve the ability to determine the yield and height of burst of nuclear explosions in the atmosphere. Necessarily there were two related, intermediate objectives: namely, to develop digital data processing techniques for detecting and analyzing signals recorded by microbarograph arrays, and to improve predictions of spectra and waveforms of acoustic-gravity waves as well as of their associated seismic surface waves.

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RAYLEIGH WAVE AND ACOUSTIC-GRAVITY WAVE SIGNALS FROM NUCLEAR EXPLOSIONS IN THE ATMOSPHERE

Final Technical Report

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I. INTRODUCTION

The detection of nuclear explosions in the atmosphere has posed few problems to the variety of techniques used to sense the resulting disturbances. Hence, the research covered by the subject contract was directed toward the extraction of intelligence from microbarographic signals. Our principal objective was to improve our country's ability to determine the yield and height of burst of nuclear explosions in the atmosphere. Necessarily there were two related, intermediate objectives: namely, to develop digital data processing techniques for detecting and analyzing signals recorded by microbarograph arrays, and to improve predictions of spectra and waveforms of acoustic-gravity waves as well as of their associated seismic surface waves.

Work under the contract began on 1 March 1969. The contract was extended three times and finally terminated on 31 March 1972. The table on the following page sets out the Work Statement, with tasks a through c designed to meet the objectives described above. Task f was designed to produce a state-of-the-art report, underlining the contributions of research under ARPA to enhancement and understanding of microbarograph data.

Prior to the undertaking of this work, the recording of microbarograph data was entirely analog and processing of the data was accomplished by analog means. Thus, the early work under the contract was revolved around the analog data. Techniques were developed to digitize the data without loss of information and digital programs were written to duplicate the analog processing techniques. As time progressed, this work evolved into the uses of data recorded digitally and of direct digital processing techniques.

The development of diagnostic parameters requires an understanding of the underlying physics. Therefore, the data processing and analysis studies were complemented with research on the basic phenomenon relating nuclear explosions to the generation of acoustic/gravity waves and of Rayleigh waves.

Results of these studies found application outside of this project even as the work was going on. Two of the most notable examples were the studies of signal and noise coherency and of f-k spectra. A knowledge of coherency properties was immediately applicable to the design of

Statement of Work	Period of Performance
a. Digitize microbaragraph array data as required for research, and as requested by the Project Scientist.	3/1/69 through 2/28/71
b. Develop computer programs for infrasonic signal detection, analysis, and data display.	3/1/69 through 2/28/71
c. Evaluate and compare the various methods for signal detection and analysis.	3/1/69 through 2/28/71
d. Conduct research in the mechanism for generation of Rayleigh waves by nuclear explosions in the atmosphere, with the objective of determining those characteristics of the Rayleigh wave signal spectrum which may be diagnostic of the yield and height of the explosion.	3/1/69 through 3/31/72
e. Conduct research in the mechanism for generation of acoustic/gravity waves in the atmosphere by nuclear explosions, with the objective of determining those characteristics of the acoustic/gravity wave spectrum which may be diagnostic of the yield and height of the explosion.	3/1/69 through 3/31/72
f. Survey and provide a critique of contracts funded by ARPA in the general field of seismic and acoustic detection of atmospheric explosions, as requested by the project officer.	3/1/70 through 3/31/72
g. Conduct other research tasks as approved by the project officer, not to exceed the estimated cost of the contract.	3/1/70 through 2/28/71

microbarograph arrays being installed on other projects; results of f-k spectral studies led to a technique which, when applied to long-period seismic data, permits us to strip off one of two interfering signals to produce a better estimate of the second signal. Unfortunately, all of our studies were not as successful. For example, we failed in our attempts to write a satisfactory program based on finite-element analysis to predict Rayleigh wave-generation by an explosion over an atoll. However, this work is continuing in a thesis program at Penn State and should eventually be successful.

The studies under this contract have all resulted in publication, either in technical journals or in Alexandria Laboratory Reports. A list of these publications, showing the related tasks in the Work Statement, is given at the end of this report. In the following pages, we have outlined the major results of the program by summarizing the pertinent reports.

II. COMPUTER PROGRAMS

Work on this project included writing some sixty computer programs, which were used in our related research and are available for use by other research groups.

We have tabulated below brief summaries of the computer programs developed by the infrasonics section of the Alexandria Laboratories, or adopted from other sources where stated. The areas covered by these programs include altering data formats, performing signal detection and analysis in the time domain and frequency-wavenumber domain, and various theoretical calculations involving the acoustic radiation from explosion sources in a layered atmosphere.

Most of the programs and subroutines are written in FORTRAN-63 language for the CDC 1604-B with some subroutines coded in CODAP, the 1604 assembly language. The data input is magnetic tape whose format is explained by Kerr (1971). The data are output to magnetic tapes. Output displays are either contour plots on the printer or standard calcomp plots.

PROGRAMS AVAILABLE ON CONTRACT NO. F-14620-69-C-0082

Info. Number	Program Name	Description
001	ESSAFORM	Reformats ESSA array data on VLR tapes into SDL unpacked library format.
002	SLIPSHOD	Reformats LASA slow-mode infrasonic data channels into SDL format.
003	WASBIT	Digital simulation of ESSA N-4 correlator for infrasonic signal detection and analysis.
004	FK2D Tape	Two dimensional wavenumber spectra at fixed frequencies.
005	VKSPTM2	Power as function of frequency and wavenumber at fixed azimuths.
006	BREEDER	Generates artifical data consisting of specified mixtures of monochromatic propagating plane waves.
007	ARESPONS	Array response in wavenumber space.
008	ANSWER	Time-varying spectrograms, power as a function of both frequency and time.
009	HASH	Far-field radiation from a point, source in earth atmosphere system.
010	HARKRIDR	Rayleigh wave radiation from a point pressure source at the surface of a layered earth.
011	BUMPY	Two dimensional curvature of frequency-wavenumber spectra and array response in wavenumber space.
012	CALCULAT	Predicts N-4 correlator output from array response in wavenumber space.
013	PHASDSPN	Adaptation of the seismic hyperfine beam-steering program to estimate signal velocity and azimuth from the correlation matrix of the data.
014	COHERENCY	Spectra matrix of multichannel data and display of cross-power spectra, coherence and phase as functions of frequency.

Info. Number	Program Name	Description
015	PIERCE	Harkrider's acoustic-gravity wave program with three dimensional winds.
016	LSQSHIFT	Hyperfine beamsteering parameters from data correlation matrix.
017	DECIMERG	Low-pass filters, decimates, and merges two consecutive standard SDL subset tape records, to facilitate study of long period records.
018	FKBYBEAM	Wavenumber spectra at fixed frequencies from the beam sum variances of band-pass filtered data.
019	DECODE	Convert AFWL data into an equivalent 1604 FORTRAN FORMAT.
020	DR-FK2DDS	Generates spectral matrixes for any frequency interval, by the Bluestein algorithm.
021	LAPLACE	Computes Laplace transform.
022	SAXIER	Instantaneous frequency and envelope of a time series, by Cooley-Tukey algorithm.
023	GRANIER	More flexible version of Info 004 which contour in decibels, centibels or milibels and permits specification of wavenumber region of plot.
024	LAMBFORM	Converts records from SDL format to VLR format to implement application of our N-4 correlator program.
025	ANSWER2A	Plots power versus time and frequency for each of several input channels and finally plots the beam-summed spectrum.
026	DECIMATE	To low-pass filter and decimate a taped digital record.
027	FILTRATE	To low-pass, high-pass, or band-pass filter digitally and output a magnetic tape record. Four- and eight-pole Butterworth filters.
028	DGH83E	A faster variation of Info 012 with facilitated input.
029	AIRPUNCH	Calculates source height excitation functions from eigenfunctions generated in program Info 010.

Info. Number	Program Name	Description
030	WAYOFF	Duplicates airwaves.
031	DGHS83	Generates seismograms of far-field Rayleigh waves from surface pressures beneath a source; from Info 35.
032	N4BEAMER	An elaboration of Info003 which minutely explores the ESSA correlator output as it generates it, and prints out a bulletin of detected signals, with time, speed, bearing, and signal-to-noise ratio.
		To generate an SDL subset magnetic tape record from a multichannel tape record in alphanumeric format (Isotopes).
033	MAGIC	Calculates the Laplacian of the array response at the origin in wavenumber space for a given array -- used in conjunction with Info 013 (BUMPY).
034	AIRROOTS	Calculates eigenvalues for normal modes of acoustic-gravity waves in a layered atmosphere.
035	MODROOTS	Calculates the real roots for airwaves.
036	AIRWAVES	Calculates theoretical pressures and velocities for atmospheric acoustic-gravity waves generated by point sources in a layered atmosphere.
037	PRSHR	Reads AFTAC tapes of SHELL computed total pressures, reduces them to excess pressures and writes them onto save tapes.
038	PLOTPRES	Outputs the excess pressures from Info048 onto the Calcomp plotter as point (x) plots.
039	PXFIX	Reads the Info048 save tapes, converts the excess pressures from functions of variable distance with time as a parameter to functions of variable time with evenly spaced distances as parameters and writes them onto new save tapes.
040	TIMEPRES	Outputs the excess pressures from Info050 onto the Calcomp plotter as point (x) plots.

Info. Number	Program Code	Description
041	PXTIM	Reads the Info 050 save tapes, fits a Glasstone pulse to the excess pressure data, samples the function at regular time intervals and writes them onto new save tapes.
042	PLOTPNDT	Outputs the excess pressures from Info 052 onto the Calcomp plotter as line plots.
043	PTRANS	Computes the Fourier transforms of the excess pressure data on Info 052 save tapes at specified distances and frequency bands and punches the resulting spectra into decks of cards.
044		A modification of Info 052 for fitting a parabola to the positive phase of the pressure pulse.
045		A modification of Info 052 for fitting by least squares a Glasstone pulse to the excess pressure data.
046	FKFAST	Calculates frequency-wavenumber spectra by a generalization of the process of Info 057. For the case of the 13 inner sensors at LAMA, this program is more than an order of magnitude faster than earlier programs.
047	RESPONSE	Calculates array response using the algorithm of Info 058, and is also more than an order of magnitude faster for 13 sensors than were earlier programs.
048	POWER	To compute power-frequency spectra; incorporates certain flexibilities such as control of the range of frequencies to plot, and calculates power in units of the time function squared.
049	MAKETAPE	Reformats specified data in packed or unpacked library format, or subset format into SDL subset format.
050	DGHS33	Modification of DGHS83, to compute Rayleigh waves for a coupled nongravitating ocean-solid earth half space.
051	PTRAN52	Modication of PTRANS, to compute the pressure spectra for spherically symmetric reflected Glasstone pulses.

Info. Number	Program Code	Description
052	FBYBEAM	Computes the F-stat[illegible] as a function of frequency and wavenumber for multichannel records.
053	BMSTR3	Modification of existing program to make multiple runs.
054	BURRIDGE	Calculates the response of a pipe array by R. Burridge, New York University.
055	CDCIBM	Translates FORTRAN languages.
056	FKPOWER	Spectral estimation from the best beams.
057	FKSEARCH	Signal search on three-dimensional half-space maxima.
058	ESSASET	Creates subset format tapes.
059	BSVI	The program computes and prints the velocit[illegible], azimuth, power, and Fisher statistic for the best beam from specific inputs.

III. SIGNAL DETECTION AND ANALYSIS

Out of our evaluation of various techniques for signal analysis, we derived a number of principles and algorithms which in themselves are important tools in signal analysis. We describe four examples.

a) Estimation of phase velocity and apparent azimuth

McCowan and Flinn (1968) described a least-squares method for estimating the N-1 interchannel time shifts between corresponding phases of a plane wavefront crossing a horizontal array of N elements. The technique made use of estimates of the interchannel time shifts based on the time lags between all possible pairs of elements as measured from the multichannel cross-correlation matrix. It was shown that this led to N/2 degrees of freedom for estimation of each of the time shifts. This technique was then applied to the estimation of the phase velocity and apparent azimuth of a plane wave propagating across a horizontal array and applied to two events (Flinn and McCowan, 1970): the Rayleigh waves from an Alaskan earthquake recorded on the seven-element UBO long-period seismic array, and the acoustic-gravity waves from a presumed explosion in the atmosphere, recorded on part of the thirteen-element microbarographic array at LAMA. Both time-domain and frequency-domain formulations of the technique were used, i.e., we used both the multichannel correlation and spectral matrices to measure the interchannel time shifts. The results suggest that the time-domain application may provide a useful algorithm for signal detection. The phase velocity dispersion results in both cases agree reasonably well with theory and with group velocities calculated by another method. Prewhitening (flattening the spectral peaks by linear filtering) was tested as a means of preventing spectral leakage from contaminating the derived phase velocity and azimuth; the results suggest that prewhitening decreases the standard error when the signal-to-noise ratio is high, but is ineffective when the signal-to-noise ratio is low.

b) A high resolution f-k estimator

We define the curvature spectrum as the two-dimensional Laplacian of a frequency-wavenumber spectrum, the derivatives being taken in the wavenumber directions (McCowan and Flinn, 1970). Results show that the method has the characteristics

of a high-resolution f-k estimator, i.e., the spectral peaks are sharper than in ordinary f-k spectra. The curvature of an array response function can give additional information about the array capability, in addition to the array response function itself. In particular, defining the <u>differential array response</u> as the curvature of the array response at $\underset{\sim}{k} = 0$, we show that this differential response predicts the angular resolution capability of an array. We conclude that if two arrays have differential responses D_1 and D_2, then their angular resolution capabilities θ_1 and θ_2 are related by

$D_1^{1/2}\theta_1 = D_2^{1/2}\theta_2$. It is shown that using the N-4 correlator signal

analysis algorithm, the azimuth resolution of four- and five-element arrays with apertures as small as 20 km is about one-tenth of a degree. The capabilities of some microbarograph arrays in current use were compared.

c. Automatic signal detection

A high speed algorithm for computation of frequency-wavenumber (f-k) spectra was developed (Smart and Flinn, 1971) and two real-time infrasonic data processing techniques that it makes possible, were described: (1) Signal detection by a search of f-k space. In comparison to the N-4 correlator, a broad-band signal detector, the f-k search with a Fisher detector has a theoretical advantage, which we verify in practice. (2) An f-k filter technique for calculating 'best beam' estimates. This technique traces the beam containing maximum power, from frequency to frequency through f-k space, and thus allows for wandering of signal velocity and arrival azimuth. This maximum power function is taken as the frequency spectrum of the best beam. In our programs the Fisher statistic of the signal estimate, and the velocity and azimuth, are computed and displayed as functions of frequency. Examples from real data for both processing techniques were processed and discussed.

d. Energy maxima in three dimensional f-k space

One of the lines of research which has had important implications in other geophysical applications, concerns the use of array data to determine the position of energy maxima in three dimensional frequency-wave number space (Smart, 1971). Algorithms which have evolved from this study are useful in separating two long period signals which traverse a seismic array at the same time but at only

slightly different azimuths.

Research on this topic was intensified when it was discovered that two-dimensional cross-sections of finite frequency-wavenumber spectra can easily be misinterpreted, since leakage of energy occurs along lines of constant wavenumber. In particular, the signal phase velocity determined from measurements on cross-sections normal to the frequency axis can be incorrect.

The array response tends to smear the power sideways along lines of constant period; the spectral smoothing function tends to smear the power vertically along lines of constant wavenumber. To estimate correctly the phase velocity of a signal, a two-stage process must be used: first, a section normal to the frequency axis is used to estimate the azimuth of the signal; second, the azimuthal section in that direction is used to estimate signal velocity. In a routine data processing procedure the azimuthal section would be formed at increments around the compass. In spite of the fact that the combined interpretation of azimuthal and k-plane sections suffices to determine phase velocity unambiguously, this procedure still has drawbacks: with spectral estimates contaminated by leakage along lines of constant wavenumber and planes of constant period, this determination by means of f-k and k-plane sections is laborious. We therefore devised a method of constructing frequency-wavenumber spectra in which the inevitable leakage occurs along lines of constant phase velocity, so that the true phase velocity will be evident in the k-plane section.

Another advantage of the beam-forming algorithm is that the halfwidth of the array response is frequency-dependent for leaked energy. Thus if a leaked component dominates a given cross-section, its frequency will be measurable on that cross-section. The relation between apparent (measured) halfwidth and frequency is that if k_2 is the main lobe half width for a given array, then the component at f' will have an apparent halfwidth of $(f_0/f')k_2$. Since f_0 (frequency at the maximum) and k_2 are known, the frequency f' may be determined by taking the reciprocoal of the apparent half-width and multiplying by f_0k_2.

IV. ACOUSTIC GRAVITY WAVES
GENERATED BY ATMOSPHERIC EXPLOSIONS

a. Theoretical models for atmospheric structure

One of the significant accomplishments of this project was the derivation of a new model for atmospheric structure, which allows faster calculation of acoustic-gravity modal excitation. The standard programs (Harkrider, 1964a) use a model atmosphere made up of isothermal layers, whereas the new model assumes layers in which the temperature varies linearly with height. Since all atmospheric structures contain large intervals of height in which the temperature varies rapidly, the isothermal layer models require many layers for an accurate fit to the structure. The modal excitation is calculated by computing the product of layer matrices a large number of times, and at each frequency several trigonometric functions must be calculated in each layer matrix. The investment in computing time is considerable.

The new method (Greenfield and Harkrider, 1971) reduces the number of layers required to fit the structure by an order of magnitude. The layer matrices require calculation of Kummer functions, which require more calculation steps than trigonometric functions, but the saving in time and storage space is still impressive.

In addition, the new formulation allows precise study of Tolstoy's (1967) prediction that strong positive temperature gradients should cause anomalous acoustic-gravity wave propagation, in that the acoustic cutoff period (the short-period cutoff) is greater than the Brunt Vaisala period. This study is being continued at the California Institute of Technology under another contract.

b. Atmospheric waves as functions of yield and height of burst

The continuing testing of nuclear weapons in the atmosphere has stimulated interest in the use of infrasonic data for diagnosing yields and burst altitudes. We calculated theoretical barograms for a variety of yields and burst heights, using programs supplied by D.G. Harkrider (1964a).

Harkrider's programs were modified to include the energy injection source described by Pierce (1968). The programs are listed in an appendix of the detailed report by Newton et al. (1972).

Using the energy injection source, theoretical spectra were computed for point sources in an ARDC model atmosphere (Wares et al., 1960), for an epicentral distance of 10,000 km. Excitation was computed for the modes which propagate in the period range of the microbarograph stations, 0.4 to 14 minutes; these include the gravity mode GR_0 and acoustic modes S_0 to S_8. The individual modes were summed to yield composite barograms.

We found that the long-period power (greater than 1 minute period) varies as the square of the yield for low-altitude explosions, and as the two-thirds power of yield for high altitudes (around 100 km). For a given yield, the long-period power increases with increasing burst height to a maximum and then decreases; the maximum occurs at lower altitudes for higher yields (Newton et al., 1972).

c. Spacial coherency of acoustic gravity waves

The coherence of atmospheric acoustic-gravity waves has been measured in the period range 10-100s at the Large Aperture Microbarograph Array in south-eastern Montana. The acoustic-gravity waves observed were signals generated by presumed nuclear explosions. The decrease of coherence with increasing distance between pairs of microbarographs is less rapid in the direction of wave propagation than transverse to it. Variation of direction of arrival over a small range of azimuth ($\pm 5°$) explains the spatial behaviour of coherence in the direction normal to the wave propagation; variation of phase velocity of ± 10m/sec explains the behaviour along the direction of wave propaga-tion. Both effects may be due to inhomogeneities in the atmosphere; the velocity variation may be due to the presence in the signal of several normal modes of acoustic-gravity waves, each travelling at a slightly different phase velocity in the range 300-330 m/sec.

V. RAYLEIGH WAVES GENERATED BY ATMOSPHERIC EXPLOSIONS

The coupling of atmospheric disturbances was considered in the Seismic Data Laboratory and the work was carried over into the subject project. The computations were performed for explosions over a half space, both water covered and solid, and for explosions over an atoll.

a. Rayleigh waves excitation over a half space

Harkrider made available to us his program (Harkrider, 1964a, 1964b) for calculating far-field modal propagation of acoustic-gravity waves in an atmosphere consisting of isothermal layers overlying a rigid half space, and a similar program for calculating Rayleigh wave modal propagation in a layered halfspace underlying a vacuum. These two programs were merged in order to model the coupling of atmospheric and seismic wave propagation, specifically the generation of Rayleigh waves by point sources in the atmosphere. It was found that the loading of the atmosphere on the solid earth affected the Rayleigh wave phase velocity, group velocity, and medium response by about the ratio of atmospheric sea-level density to the density of the earth's crust, i.e., about 0.01 percent.

The suite of programs used in this project to predict Rayleigh wave excitation are described by Kerr (1971). In the first program segment, the atmospheric eigenfunctions are calculated and used to construct the source-height excitation function. Then the actual far-field Rayleigh waveforms were synthesized by the Aki algorithm (Aki, 1960), using the source exitation and assumptions about the solid earth response and Rayleigh wave dispersion characteristics. In the research reported here we used two basic earth models: the Gutenberg continental model, which has a low-velocity zone (Ben-Menahem and Harkrider 1964, p. 2610) and the Anderson-Toksöz oceanic model (Harkrider and Anderson, 1966, p. 2970). Earth and atmospheric layering characteristics were as usual assumed constant between source and receiver.

Calculations were made using a wide variety of source heights and yields. Several types of sources were used: mass-injection sources (Harkrider and Flinn, 1970), energy-injection sources (Pierce, 1968), and scaled surface overpressures (Murphy, 1971). In another report we showed (Harkrider et al.,1972) that the energy-injection source is the most reasonable of those source types. Waveforms

and spectra were calculated for yields of 1 kT to 10 MT at burst heights of 0.30 to 80 km.

These calculated data were then analyzed to compare source types, and to find characteristics of the waveforms and spectra which might be diagnostic of burst height and yield.

Our conclusions are:

A. Source type:

1. For the generation of Rayleigh waves, the mass-injection and energy-injection sources are equivalent.

2. The Rayleigh wave amplitude for source heights of a few kilometers are independent of source type. For intermediate altitudes the surface overpressure source predicts greater Rayleigh wave amplitudes than the mass or energy injection sources.

B. Earth model:

1. The energy coupling from the atmosphere into seismic waves is more efficient for the continental structure than for the oceanic structure, except for burst heights of 10 and 50 km.

2. The source altitude where most efficient energy coupling occurs (this altitude is yield dependent) is about 20 km higher for the oceanic structure than for the continental structure.

C. Yield-height diagnostics:

1. The waveform peak amplitude is more dependent on yield than on burst height. It is not practical to attempt to relate the peak amplitude to some power of the yield, since the exponent is dependent on the yield as well as on the burst height: see our more detailed discussion in Harkrider et al. (1972).

2. The spectral splitting ratio $\langle R \rangle_T$ (i.e., the ratio of spectral energy above period T to the energy below period T) also depends on both yield and burst height. For a given splitting period, the splitting ratio can be used to reject certain source characteristics (e.g., for T = 22 seconds, when the splitting ratio is greater than unity, the yield cannot be less than 200 kT).

3. The spectral splitting ratio spectrum: This is simply $\langle R \rangle_T$ plotted as a function of the splitting period T. These spectra are similar for all yields at a given burst height, but have distinct shapes for different burst heights. Unfortunately, the variation of these spectra with burst height is irregular, and it does not appear possible to make predictions for heights which were not included in our calculation grid.

VI. RAYLEIGH WAVE EXCITATION OVER AN ATOLL

The Rayleigh waves generated by an atmospheric explosion over an island atoll are not easy to study analytically: coupling of energy from the source into the earth takes place over the shallow water in the middle of the atoll, but a transition takes place, well within the critical distance for Rayleigh wave development, to the deep ocean whose properties determine the spectrum of the waveform recorded at large distances. Approximate theoretical coupling techniques are hence inapplicable.

Consequently, we undertook to study numerical approximations to the equations which describe wave propagation in inhomogeneous media. The first step was to use a finite difference approximation, in which time and space derivatives of the wave functions and the material properties are approximated by differences. After a large amount of effort and computer time, and lengthy discussion with mathematicians and seismologists who have been working in this field for several years, it became clear that the problem at hand is beyond the present state of the art of finite difference calculations. Workers such as Alterman and Karal always deal with problems in which the source time function is slowly varying (with respect to the time mesh size), and the material properties vary smoothly and gradually, and it turns out that the reason is that abrupt material discontinuities, and shock wave inputs -- especially at discontinuous surfaces such as the water surface -- cannot be handled satisfactorily by this method.

Consequently, we turned to a more sophisticated procedure, the finite element scheme. In this approximation the material is divided into small or large homogeneous polygonal elements, which are welded together along their edges. The elastic wave equation is solved analytically in each element, under the single assumption that the displacement components vary linearly along the edges of each element. The method works because the displacements at the vertices, as calculated within each of the contiguous elements, must all be the same. This fact leads to condition equations which can be solved straightforwardly. A static problem is solved at each time step, and the result is used as input to the next time step.

By a literature search at DDC, we located a highly sophisticated finite element program - SLAM - which had been

developed for the Air Force by the Illinois Institute of Technology. We obtained the program documentation -- five inches thick -- and studied the program during a nine-month delay waiting for the program deck itself. When it arrived, we found that it was an older version written for the CDC 6600, and contained many errors -- both logical errors and elementary FORTRAN mistakes. It was clear that what we received was not a working version of the code, and we were unable to obtain a working version despite repeated attempts.

Part of the program was written in CDC 6600 assembly language, so we obtained an in-house terminal to that type of machine, and proceeded to correct the program and experiment with it on problems whose solutions are analytically known. The total delay involved in obtaining the program and getting it working was clearly less than would have been required to develop such a program from scratch.

Several modifications were made to the program: we made it possible to vary the time-step acceleration between time steps; a general implicit scheme was installed, and finally, a fundamental error involving the boundary at the free surface was detected and repaired. The last involved the fact that although the total force on each of the node points at the free surface vanished identically, the vertical and radially tangential stresses did not. Of course, the seismic boundary condition is that the stresses vanish.

The results obtained within the contract period were disappointing. One-dimensional problems were solved correctly, but the simplest two-dimensional problems (say, a line source over a homogeneous halfspace) gave answers which did not agree with analytically known solutions. Arrival times of P, S, and Rayleigh waves were correct, but the Rayleigh wave was followed by long ringing oscillations which are clearly artifacts. The reason for the ringing is not understood.

Further work on this program and its problems is being continued under another contract at the Pennsylvania State University.

VII. PUBLICATIONS DESCRIBING RESEARCH SPONSORED BY THIS CONTRACT

Demuth, H.P., 1969, Digitizing microbarograph data: Alexandria Laboratories Report AL-69-1, Teledyne Geotech, Alexandria, Virginia.

Flinn, E.A. and McCowan, D.W., 1970, A least-squares procedure for direct estimation of azimuth and velocity of a propagating wave: Alexandria Laboratories Report AL-70-1, Teledyne Geotech, Alexandria, Virginia.

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